

components, including metals. An important aspect is the cost-effectiveness of such solutions: sludge utilization reduces disposal costs and allows for additional production.

To minimize the environmental impact of thermal power plants, it is advisable to implement recycling water supply systems, reuse treated wastewater, modernize treatment facilities, and improve the regulatory framework for industrial waste management. An integrated approach to wastewater treatment and sludge disposal will help achieve environmental safety and sustainable development of the energy sector.

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ENVIRONMENTAL ASPECTS OF SOLAR ENERGY IN THE CONTEXT OF UKRAINE'S SUSTAINABLE ENERGY RECOVERY

Amid Russia's military aggression against Ukraine, issues of energy independence, ecological security, and energy sector modernization have become critically important. Solar energy, as a leading area of "green" transformation, has significant ecological potential that aligns with sustainable development goals and the post-war energy model.

Prior to Russia's full-scale invasion, Ukraine had seen a steady increase in the share of renewable energy sources (RES) [1]. However, due to the ongoing military actions since February 24, 2022, more than 30% of solar power plants were destroyed. Damaged solar panels require proper recycling, and the recovery of Ukraine's energy infrastructure will include expanding consumer access to clean energy [2]. Expanding solar energy production is key to reducing emissions.

According to projections by the International Renewable Energy Agency (IRENA) [3] and the International Energy Agency (IEA) [4], global photovoltaic waste will reach 1.7-8 million tons by 2030. These are modules that have reached the end of their service life (25-30 years) or were prematurely removed due to the replacement of outdated equipment, mechanical panel damage, etc. The process of recycling used solar equipment is not complex. Between 85% and 95% of the materials in a solar panel can be recovered and recycled. Damaged or degraded panels should be repaired. A crystalline silicon panel consists of 76% glass, 10% polymer materials, 8% aluminum, 5% silicon semiconductors, 1% copper, and less than 0.1% silver, tin, and lead. In thin-film modules, the glass content is much higher—89% (CIGS) and 97% (CdTe). Glass, copper, lead, aluminum, and hazardous semiconductor materials must be recycled through a combination of mechanical and chemical processes that have minimal environmental impact. These materials should ideally be melted down or sold for use in new solar panels or other electronics, which will help reduce the energy required to produce them. The proposed approach offers not only ecological but also economic benefits. Currently, in Europe, 65-70% of the materials used in solar modules are reclaimed for reuse, in compliance with the EU WEEE Directive [5]. The European Committee for Electrotechnical Standardization (CENELEC) has developed additional standards for the collection and recycling of panels (EN50625-2-4 and TS50625-3-5), which include requirements to reduce pollution, minimize emissions, and promote the increase of reclaimed materials and deep recycling.

Global experience in recycling solar panel waste and the rational use of land is vital for Ukraine, as the ecological impact of recycling used and damaged PV modules is significant, and solar elements contain toxic substances harmful to the environment. Therefore, during the post-war reconstruction of Ukraine's energy sector, special attention should be paid not only to the development of solar energy but also to the recycling of photovoltaic elements and the rational use of land for the installation of solar power plants. This approach will help prevent the placement of potential waste in landfills, reduce carbon emissions through the reuse of photovoltaic panel components, and lower the cost of electricity generated by solar power plants.

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